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Review article

Anthropogenic earthquakes in the UK: A national baseline prior to shale exploitation

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ABSTRACT

We review the distribution, timing and probable causes of ~8000 onshore UK seismic events between the years 1970–2012. Of 1769 onshore seismic events with local magnitudes (M_L) ≥ 1.5, we estimate at least ~21% of these have an anthropogenic origin, at least ~40% were natural and ~39% have an undetermined, anthropogenic or natural origin. The majority of the anthropogenic related earthquakes were caused by coal mining and the decline in their numbers from the 1980s to the 2000s was concurrent with a decline in UK coal production. To date, two earthquakes with $M_L \geq 1.5$ have been caused by hydraulic fracturing. We have a high level of confidence that the mean number of anthropogenic related earthquakes ($M_L \geq 1.5$) per year onshore in the UK since 1999 is at least three with an annual range of between zero and eight. If we assumed that 50% of the undetermined events had an anthropogenic origin the mean per year increases to twelve. Although there are inherent uncertainties in assigning an anthropogenic versus natural cause for historical earthquakes, these values provide a baseline for the UK, the first of its kind for any nation state, in advance of the presently planned shale gas and oil exploitation.

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1. Introduction

Fracking (hydraulic fracturing) is a process used to recover oil and gas from low-permeability unconventional reservoirs. The technology has generated significant public debate because of potential environmental hazards associated with it. One of these hazards is the risk of inducing or triggering felt earthquakes (e.g. Davies et al., 2013). For example felt earthquakes attributed to the process of fracking have been documented in Canada, the United Kingdom (UK) and the United States of America (USA), with maximum magnitude events of 4.4, 2.3 and 2.9 respectively (de Pater and Baisch, 2011; Holland, 2013, BCOGC, 2014).

Since the development of a significant UK shale gas and oil industry is now under discussion, research on the history, distribution and number of anthropogenic earthquakes is timely and important. Establishing a baseline for the number of anthropogenic earthquakes that occur each year is useful prior to the potential exploitation of shale reservoirs. Used along with other criteria, in the future it may help establish if fracking has become responsible for a nationwide increase in seismic activity. This UK-wide review could be augmented by similar, more detailed local studies where fracking is planned. The review also serves as a case study for other nation states considering the use of this technology or where it is already deployed. Furthermore this review provides context for the UK debate around anthropogenic related seismicity and shale reservoir exploitation, in terms of an assessment of the magnitudes and frequencies of induced or triggered earthquakes that the UK has experienced in recent history, prior to the exploitation of shale reservoirs.

Here we review the recent history of UK seismic events between the years 1970–2012 and categorise events as natural, anthropogenic or undetermined. Our study is the first to produce an overview of the UK's history of anthropogenic related earthquakes. We conclude by proposing the first national baseline for the number of anthropogenic earthquakes with local magnitudes (M_L) $\geq$ 1.5 that would be expected to occur per year, prior to the potential stages of shale exploration, development and production.

2. Data and method

We used the British Geological Survey (BGS) catalogue of 10,457 seismic events recorded in the period 1970–2012 (Baptie, pers. comm.). Events were divided into those that were located onshore and offshore. We excluded those detected in French, Danish and Norwegian territories which took the number of events in our study to ~8000. For most events the catalogue provides local magnitudes and estimated hypocentre depths, but for some events these were not available and therefore such events have been excluded. Detected seismic events in the UK have the following origins:

1. Natural earthquakes.
2. Mining related earthquakes.
3. Hydraulic fracturing.
4. Geothermal energy – thermal fractures.
5. Industrial explosions (e.g. quarry blasting).
6. Meteorological phenomena (e.g. lightning strikes).
7. Cultural sources (e.g. heavy vehicles passing, sonic booms from military aircraft, weapons testing and rock concerts).

The BGS aims to exclude the last three types of event from their database. This is done by using the character, location and precise timings of these events and excluding them by contacting the relevant organisations (Galloway, 2012). We cannot be certain that all such cases have been removed from the database. For this reason, we refer to the entries in the BGS catalogue as "events" and not "earthquakes". Of the ~8000 onshore events in this analysis we focussed on 1769 with $M_L \geq 1.5$.

Since 1993 there have been seven generally accepted criteria that should be met before an earthquake is considered to be of anthropogenic origin (Davis and Frohlich, 1993):

1. Are the events the first known earthquakes of this character in the region?
2. Is there a clear temporal correlation between injection and seismicity?
3. Are the epicentres within 5 km of injection wells?
4. Do some earthquakes occur at or near injection depths?
5. If not, are there known geologic structures that may channel flow to sites of earthquakes?
6. Are changes in fluid pressures at well bottoms sufficient to encourage seismicity?
7. Are changes in fluid pressures at hypocentral locations sufficient to encourage seismicity?

Applying these criteria in the UK setting is not straightforward. These criteria are mainly relevant to inducing or triggering an event due to fluid injection, rather than due to mining activity. The UK has a long history of mining activity and the criteria of spatial or temporal coincidence can be applied to mining related events as it is to injection related earthquakes. However, one has to be aware that long-range triggering of earthquakes can occur due to fluid injection in a pre-stressed heterogeneous medium due to poro-elastic effects (e.g. Maillot et al., 1999). These events may eventually occur some tens of kilometres away from the perturbing source (Keranen et al., 2014).

It is not possible to apply these seven criteria robustly to the ~8000 events in the BGS catalogue due to insufficient information.

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Therefore our statistics are initial estimates of those that are anthropogenic versus natural based upon the following considerations:

1. We considered peer reviewed research papers and other published literature on events. We have not cited these papers here, but to give one example King (1980) suggests a natural fault plane focal mechanism for the 26 December 1979, Carlisle earthquake.
2. Foreshocks, aftershocks and swarms of events were assigned based on published literature, BGS determinations, locations and times of occurrence.
3. We considered any spatial coincidence with coalfields, collieries and mining towns.
4. We considered the hypocentre depth and local magnitude. Based on published examples, anthropogenic related events in the UK are typically < 3 km depth (shallow) and less than ~M_L 3.0.

Whilst we have used hypocentre depth in conjunction with other factors for categorising anthropogenic events, we have not applied a specific depth (e.g. the depth of the deepest coal workings) below which we consider earthquakes to only be natural. This is because hypocentre depth can be several kilometres in error (e.g. Galloway, 2012, their table 1). Because of a paucity of detailed information for some of the events, those that had an undetermined origin were classified as “undefined” in the statistics. Additional work might be able to resolve these cases.

3. Earthquake classification terminology

Natural earthquakes are those for which there is no evidence for anthropogenic influence. These earthquakes occur when natural tectonic forces exceed the resisting frictional forces on existing faults or exceed the strength of a non-fractured rock. Triggered earthquakes are those that result from a small anthropogenic perturbation shifting a system from a near-unstable state to a fully unstable one. Examples include earthquakes that result from fault reactivation after fluid injection (e.g. de Pater and Baisch, 2011). Earthquakes can also be caused by natural processes that impose rapid stress loading on an already near-unstable fault system. Such processes include strong surface waves generated by large earthquakes (Hill et al., 1993), solid Earth tides (Métivier et al., 2009), rain and snow melt that alter the hydrology (Saar and Manga, 2003), pore pressure changes (Sigmundsson et al., 1997) and geothermal and volcanic activity (Foulger, 1982). Since these are natural processes, we classify such earthquakes as “natural”. “Induced” earthquakes are those where external anthropogenic activities cause stress and failure within a rock not close to natural failure. Earthquakes produced by hydraulic stimulation, including both fracking and the creation of Enhanced Geothermal Systems (EGS) can be either triggered or induced.

The key distinction we draw between triggered and induced earthquakes is that triggered earthquakes result from an anthropogenic disturbance releasing largely pre-existing natural stresses. The disturbance then provides the final, small increment of stress that results in the earthquake nucleating. Triggering of earthquakes fits well with the hypothesis that faults in the Earth's crust are critically stressed (Townend and Zoback, 2000). Small increases in fluid pressure (e.g. fluid injection) can result in disequilibrium and faults subsequently fail in order for the crust to regain a failure equilibrium state. Anthropogenic triggering may be thought of as causing the earthquake to occur earlier than it would otherwise have done. However, it is not possible to determine with certainty how or when the natural stresses would have been released had the triggering mechanism not occurred.

The circulation of pressurised fluids can be fundamental to fault creation or failure and the nucleation of earthquakes. The failure condition is commonly expressed as a critical shear stress (τ_{crit}) and the equation:

$$\tau_{crit} = \mu(\sigma_n - P) + S_o \tag{1}$$

where μ is the coefficient of friction (0.6–1.0), σ_n is the applied normal stress, P is the pore fluid pressure and S_o is a constant related to the cohesive strength of the material or sliding surface. Changes in the hydrogeological framework can increase pore fluid pressure (P) and reduce effective stress (σ_n−P), allowing pre-existing critically stressed faults to slip. Triggered earthquakes are typically larger in magnitude than induced earthquakes. This is because the stored natural tectonic stress released by the trigger is generally much larger than that of purely anthropogenic origin. Such triggered earthquakes can be up to 5.7 in magnitude in the case of waste-water injection (Keranen et al., 2013), but are still significantly lower than those events that can occur at active plate boundaries. It should be noted that effective stress is a relative term. If normal stress is sufficiently large, pore pressure increases from anthropogenic fluid injection may have little effect. Therefore the prediction of triggering earthquakes is complicated and uncertainties remain large.

A common misconception is that small magnitude earthquakes (e.g. M_L ~2.0) cannot be felt. However, the surface effects of an earthquake are a function of the energy released by the earthquake, the depth of the earthquake and the geological overburden composition. For example, a deep earthquake releasing large amounts of energy can result in the same felt surface effects as a shallower earthquake releasing less energy, primarily due to more geometrical spreading of the released energy from the deeper hypocentre location. Consequently, measuring earthquake magnitude based on surface effects can be ambiguous. Local magnitudes are not a measure of surface effects, they are a measure of the energy released by an earthquake. Although moment magnitude (M_w) scale is the preferred magnitude scale of seismologists, local magnitude was the only magnitude available in the BGS catalogue and was therefore used for this study. In studies in mining areas, after a period in which populations become more sensitised, it is common for events of M_L 1.5 to be reported. In some circumstances events as low as M_L 1.0 have been reliably reported (Bishop et al., 1993).

4. The UK seismic monitoring network

National seismic monitoring in the UK by the BGS started with the Lowlands Seismic Network (LOWNET), which was installed in Scotland in the late 1960s and early 1970s. It included seven stations (Fig. 1). These were supplemented by other stations and arrays across the UK and Ireland (Crampin et al., 1970). The network was expanded in 1976 to improve detection and location accuracy outside of Scotland. Subsequently, the number of seismic stations steadily increased, peaking at 146 stations in the late 1990s (Baptie, 2012). The BGS is currently upgrading the network to broadband instruments and adding strong-motion-accelerometers. By the end of 2012 these numbered 38 and 26 respectively (Baptie, 2012). The UK onshore catalogue from 1979 is complete for $M_L \geq 2.5$. Prior to this, and dating back to 1970, it is only complete for $M_L \geq 3.5$ (Galloway, 2012). Since the late 1980s the onshore detection threshold has been ~ M_L 1.5 (note that section 8 suggests a revised threshold of M_L 1.4) and the event catalogue is considered complete for this magnitude and above. As the numbers and distribution of seismic events with M_L < 1.5 can be significantly affected by seismic station location, we have

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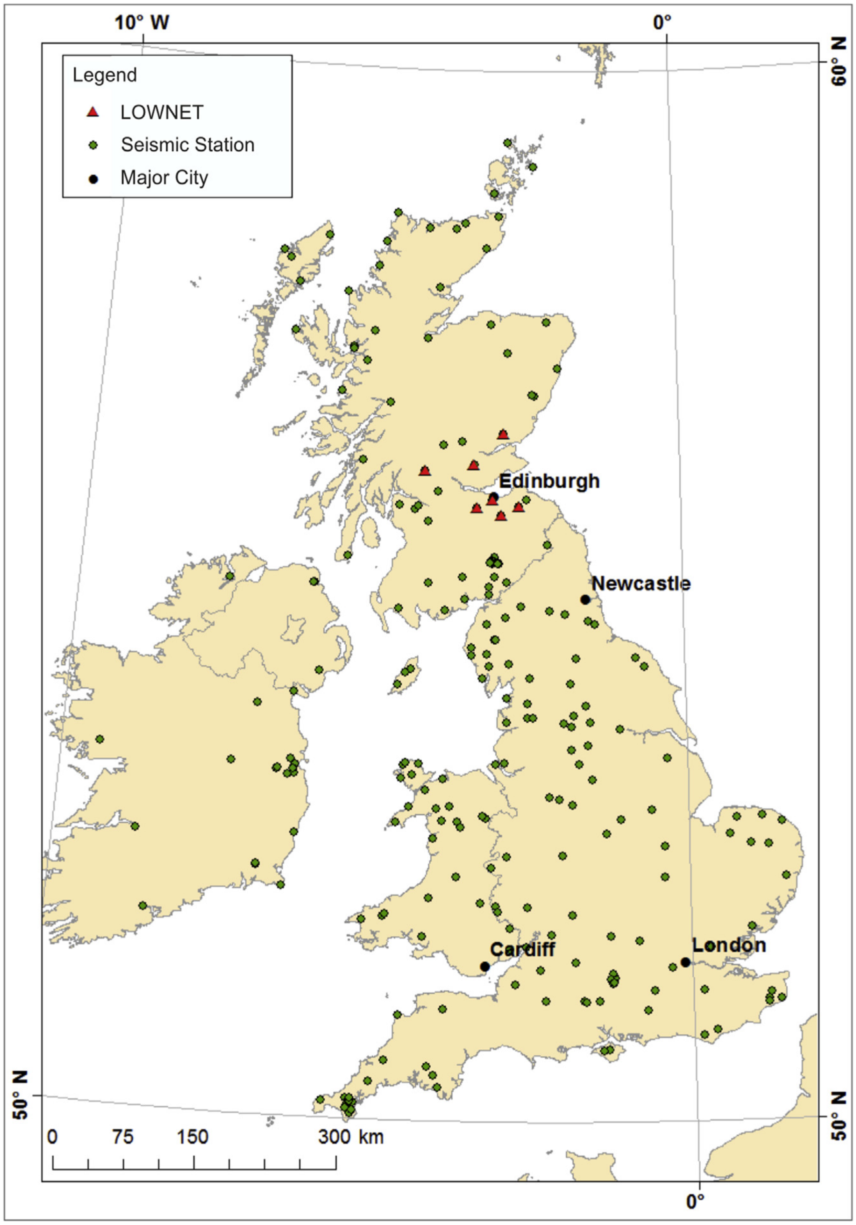

Fig. 1. UK seismic stations in 2012.

excluded these events from the main analysis. The relatively low magnitude threshold of M_L 1.5 is helpful in terms of the monitoring of possible fracking related earthquakes.

UK seismicity is not uniformly distributed (Fig. 2). Many natural earthquakes are associated with known fault zones, such as the Aberfoyle earthquake swarm of 2003 which occurred in the Highland Boundary Fault Zone (Ottemöller and Thomas, 2007). In addition to natural earthquakes, the UK has experienced numerous anthropogenic earthquakes, mostly caused by coal mining (Fig. 3) (Kusznir et al., 1980; Westbrook et al., 1980; Redmayne, 1988; Bishop et al., 1993; Redmayne, 1998; Donnelly, 2006).

5. Natural seismicity in the UK

The UK does not lie on a major active plate boundary, but it is dissected by large faults originating from the Caledonide and Variscan orogenies (Rawson and Brenchley, 2006). For example, the Wem-Bridgmere-Red Rock Fault located in northwest England has a cumulative throw (vertical displacement) > 4 km (Chadwick, 1997). Natural UK earthquake activity rarely impacts members of the public, buildings or industrial infrastructure, although larger earthquakes may make national news (e.g. the M_L 4.2 Ramsgate earthquake, Kent, 22nd May 2015). Research attempting to directly relate natural earthquake distribution (Fig. 3) to geological features has met with only limited success (Chadwick et al., 1996). The current leading hypotheses for the causes of natural UK seismicity are summarised below.

5.1. Pre-existing weaknesses and the Mid-Atlantic Ridge (MAR)

The continental crust of the UK is heterogeneous with both horizontal and vertical structural elements. These are the end result of many episodes of lithospheric deformation and a long and complex tectonic history (e.g. Woodcock and Strachan, 2009). These structural heterogeneities may be weak zones on which failure may occur after stress build-up. Regional stresses in the UK

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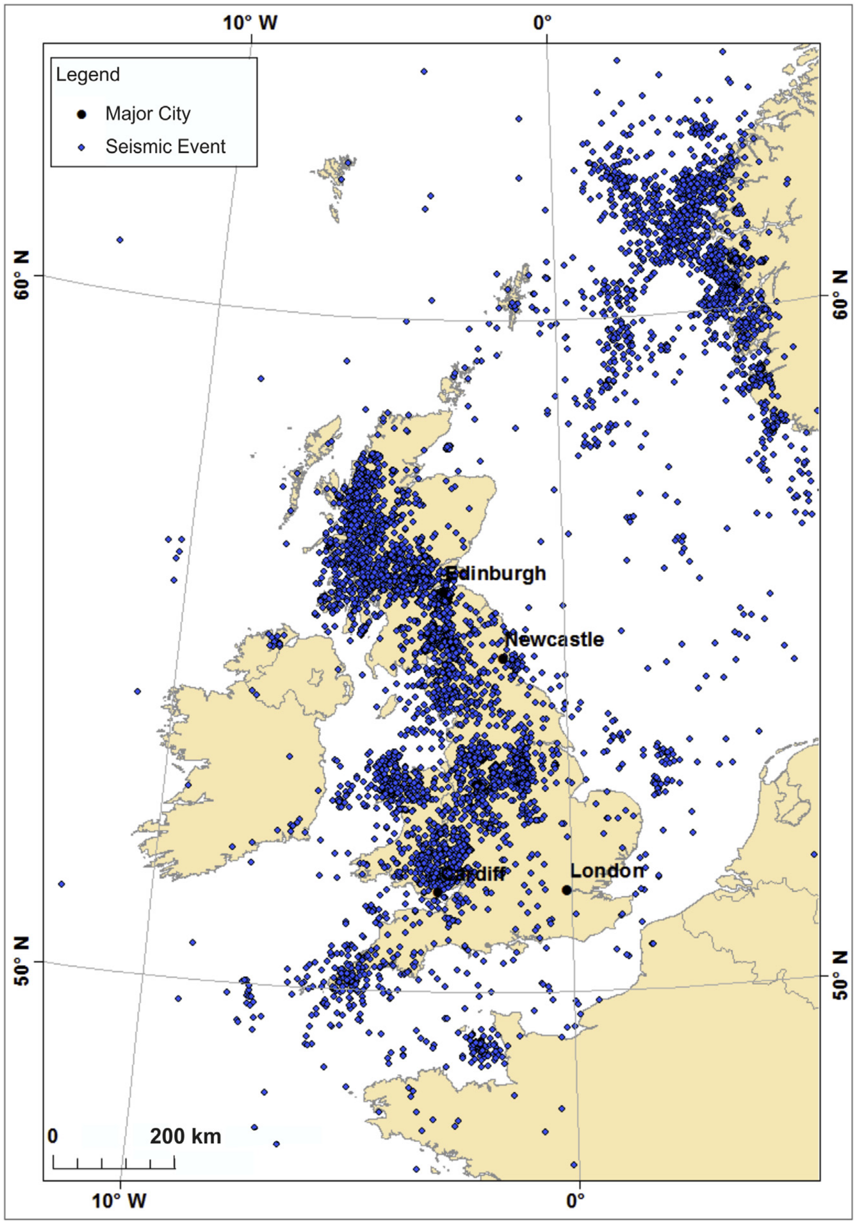

Fig. 2. Map of the UK and surroundings showing all of the 10,457 detected seismic events in the BGS catalogue for the period 1970–2012.

may arise from "ridge push" forces associated with gravitational effects at the MAR (Bott, 1991; Baptie, 2010). Modelling of ridge push predicts a maximum regional horizontal compressive stress orientation of northwest-southeast for the UK (Gölke and Coblentz, 1996). Focal mechanisms of onshore UK earthquakes with $M_L > 3.0$ have been shown to orientate consistently with these ridge push related stresses (Baptie, 2010). The best fit results (Table 1) give

Table 1
Best fit results of the principal stress axes (σ_1, σ_2 and σ_3 are the maximum, intermediate and minimum axes, respectively) and the maximum horizontal compressive stress (S_H) orientation for England, Wales and Scotland. The principal stress axes are given as azimuth/plunge. The azimuth of stress axes are given in degrees E of N and the plunge as degrees from the horizontal. The maximum horizontal compressive stress has a plunge of 0° (from Baptie, 2010).

Region	σ_1	σ_2	σ_3	S_H
England and Wales	320/3	69/80	229/9	139
Scotland	162/71	14/17	281/9	168

regional stress orientations that indicate England and Wales are best described by a compressive strike-slip tectonic regime whereas Scotland experiences east-west extension from a combination of ridge push and glacial isostatic adjustment (Baptie, 2010). Further support for a maximum regional horizontal compressive stress orientation of northwest-southeast for the UK comes from the World Stress Map project (Heidbach et al., 2008). Thus the MAR, combined with pre-existing weaknesses and crustal heterogeneity in the UK, may be the dominant controlling factor for the distribution of onshore UK earthquakes.

5.2. Isostatic glacial rebound

The solid Earth responds to glaciation by subsiding and isostatically rebounding (Jamieson, 1865). During the last glaciation considerable areas of the UK were loaded with ice (Chiverrell and Thomas, 2010). Much of this had melted by 13,000 years ago (Firth and Stewart, 2000). However, Scotland experienced a later

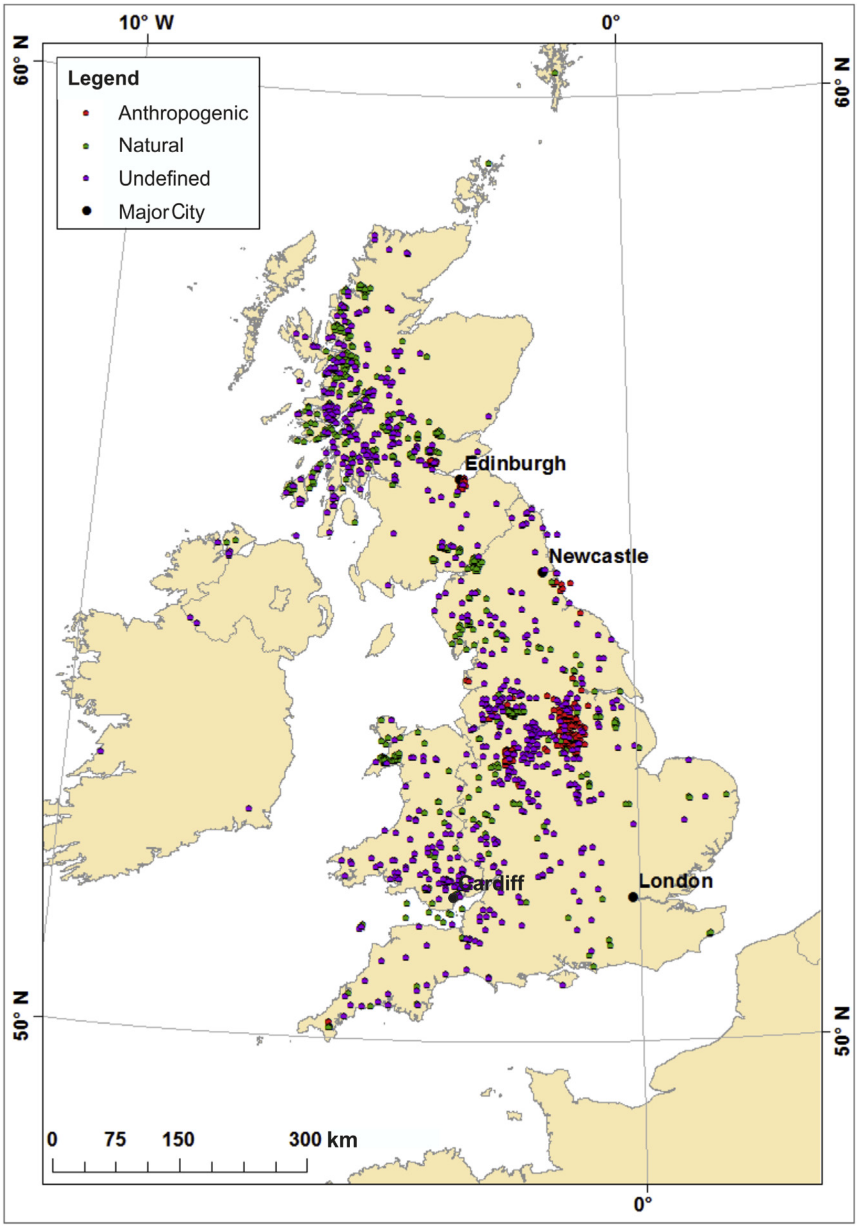

Fig. 3. Map of the UK and surroundings showing the 1769 onshore seismic events with $M_L \geq 1.5$ for the period 1970–2012 categorised in this study as anthropogenic (red), natural (green) and undefined (purple). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

period of renewed ice growth known as the Younger Dryas (Golledge, 2010). The distribution of Younger Dryas ice fits well with the distribution of earthquakes in western Scotland (Fig. 4a), leading to the hypothesis that Scottish seismicity is dominantly controlled by glacial unloading (Musson, 1996). This theory was taken further by Muir-Wood (2000) who introduced the term “deglaciation seismogenesis”. Muir-Wood (2000) proposed that a radial stress pattern results, with both extensional and compressional strain quadrants that may be seismically active or inactive (Fig. 4b and c). There are a number of problems with this hypothesis (Muir-Wood, 2000; Musson, 2007):

1. The fit of the seismic and aseismic quadrants to historic earthquakes is not good in all cases, for example in northwest Scotland and southeast England.
2. It is not explained why the forebulge zone should be larger than the rebound dome.
3. Focal mechanisms do not show what is predicted. If glacial unloading were the dominant controlling factor for seismicity, focal mechanisms would be predominantly dip-slip. They are predominantly strike-slip. This conversely suggests that horizontal forces are the dominant controlling factor.

The misfit of the focal mechanisms in particular essentially rules out isostatic glacial rebound as the dominant controlling factor for seismicity in Scotland, though it may play a minor role (Musson, 2007; Baptie, 2010). Glacial rebound is also unlikely to be a dominant controlling factor for the rest of the UK.

5.3. Mantle dynamics

The upper mantle beneath the UK and Ireland has been imaged using seismic-tomography and surface-wave studies (Goes et al., 2000; Pilidou et al., 2004; Arrowsmith et al., 2005; Pilidou et al.,

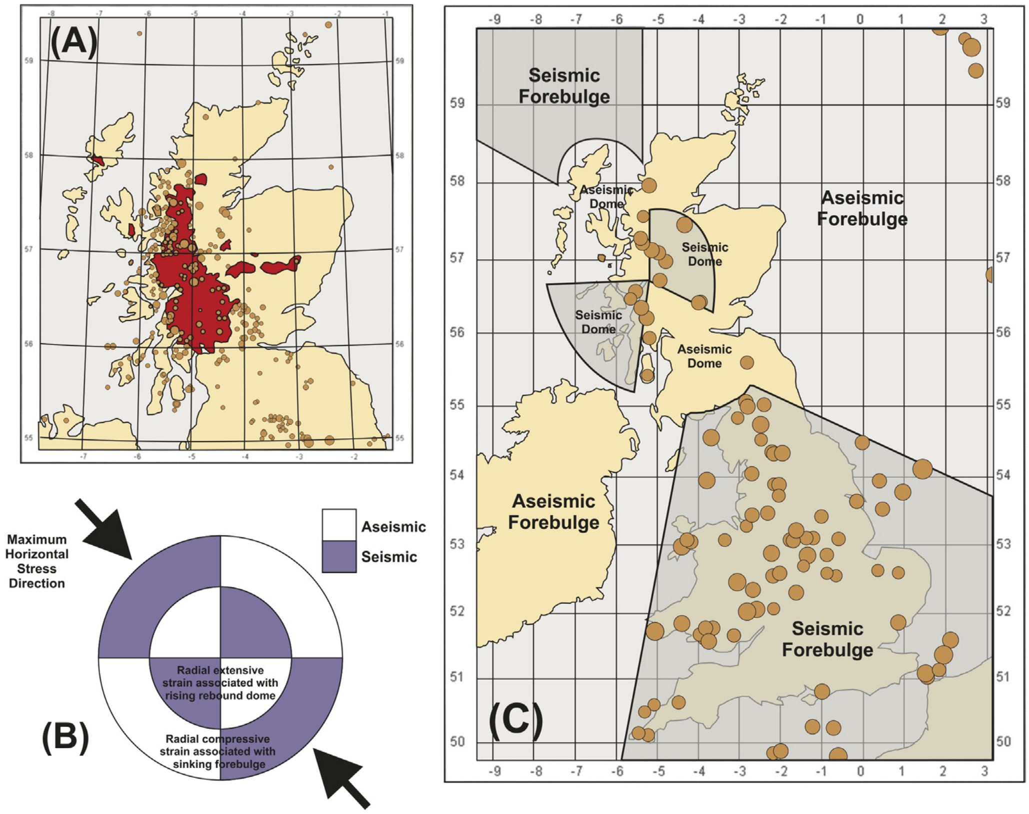

Fig. 4. (a) Scottish seismicity (earthquake epicentres orange circles) and the extent of the Younger Dryas ice cap (red) (after Musson, 2007). (b) Radial strain quadrant scheme of Muir-Wood (2000) for deglaciation seismogenesis theory (after Musson, 2007). (c) Seismic and aseismic quadrants for deglaciation seismogenesis (Muir-Wood, 2000) applied to historic UK earthquakes with M_L >4.0 (orange circles) (after Musson, 2007). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2005; Amaru et al., 2008; Wawerzinek et al., 2008; O'Donnell et al., 2011). Material with low seismic velocity in a relative sense has been attributed to plume material, with suggested links to onshore UK seismicity (Bott and Bott, 2004). However, the material is not low-velocity relative to the global average and thus provides no evidence for elevated temperatures and plumes (Foulger et al., 2013). Any link with UK seismicity is thus speculative.

6. Anthropogenic seismicity in the UK

Using the criteria outlined in Section 2 we subdivided the 1769 events with $M_L \geq 1.5$ into natural, anthropogenic and undetermined (Table 2 – online supplementary material). In the following sections we review the causes of the anthropogenic related events.

6.1. Coal mining

The UK has a long history of coal mining, long pre-dating the Industrial Revolution of the 19th Century (Bell et al., 1988). The link between coal mining triggered fault reactivation, gallery collapse and seismicity has been known for at least the last 150 years (Redmayne, 1988; Bishop et al., 1993; Redmayne, 1998; Donnelly, 2006). Following the implementation and expansion of LOWNET it quickly became apparent that coal mining related earthquakes were common throughout the UK (Fig. 5). By the mid-1980s it was believed that 25% of all detected UK seismic events (no M_L 1.5 cut-off applied) were coal mining related (Browitt et al., 1985). Our analysis of the data suggests this could be at least ~33% for 1985 (Fig. 6).

Using the method already outlined, our analysis of the BGS seismic event data suggests that the percentage of coal mining related earthquakes with $M_L \geq 1.5$ for 1970–2012 was at least ~21% (Fig. 7). The M_L 1.5 cut-off we have applied here prevents bias towards the densified seismic networks in coalfields. It might be expected that the percentage of coal mining related earthquakes with $M_L \geq 1.5$ would be higher than ~21% considering the higher levels of coal mining in the 1970s (Fig. 8). However, this is not observable in the seismic event data, presumably because of poorer detection capabilities during that period and therefore an incomplete event catalogue. By the 1980s the network was considerably larger with improved detection and location capabilities. The deployment of seismic stations in England revealed that high numbers of coal mining related earthquakes were occurring in the Derbyshire, Nottinghamshire and Staffordshire coalfields (Fig. 5). Even after accounting for the variation in detection threshold with time, it is likely that there is a correlation between coal mining related seismicity and tonnage of coal produced (Fig. 8).

There was a significant reduction in coal mining related earthquakes from 1991 to 2012. Such a decline probably results from the significant decline in UK deep coal mining during this period (Fig. 8). The number of earthquakes with $M_L \geq 1.5$ related to coal mining has dropped from 46 in 1991 to 4 in 2012, or > 90% (Figs. 8 and 15). During this period coal production declined by ~82%. This relationship and local correlations between coal mining and seismicity (Bishop et al., 1993; Kusznir et al., 1980; Redmayne, 1998; Westbrook et al., 1980) strongly support a link between historic UK coal production and anthropogenic seismicity.

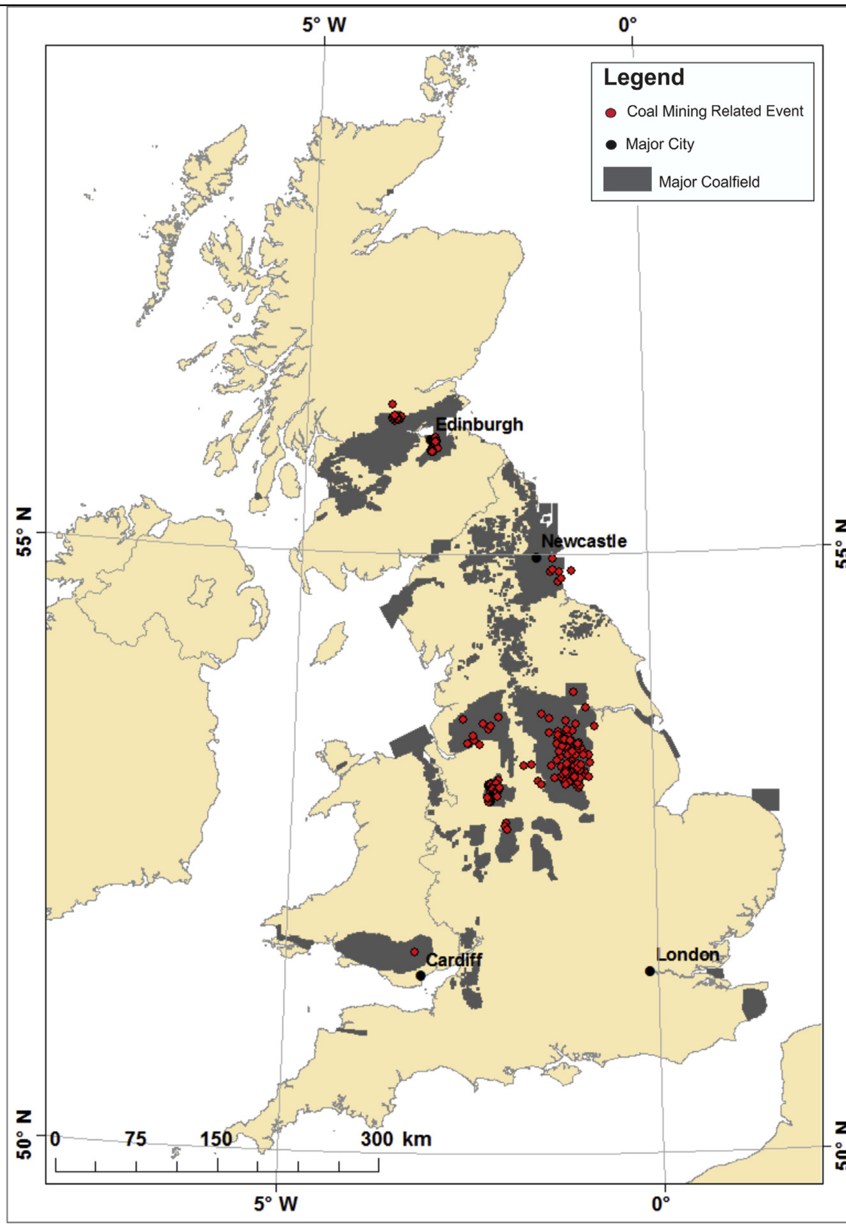

Fig. 5. Map of the UK showing 369 coal mining related events with $M_L \geq 1.5$ (red) for the period 1970–2012. They spatially correlate with several major coalfields (dark grey), including Central Scotland, Midlothian, Durham and Northumberland, Nottinghamshire, Derbyshire, Staffordshire and South Wales. Coalfield locations from the UK Coal Authority (DECC, 2015a). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

6.2. Conventional petroleum extraction

The extraction of petroleum and fluid injection for secondary recovery has induced or triggered seismicity, with the first globally documented example from 1925 in the Goose Creek oil field, Texas (Yerkes and Castle, 1976). Since this first recognition, numerous worldwide examples of induced or triggered seismicity due to reservoir compaction and fluid injection have been documented and reviewed (McGarr et al., 2002; Davies et al., 2013). To our knowledge none of the 1769 events onshore are caused by water injection into conventional petroleum reservoirs or due to reservoir compaction.

Most of the UK's petroleum production, as well as that from neighbouring Norway, Denmark and the Netherlands, has come from the North Sea and it too has caused seismicity. The Ekofisk oil field in the Norwegian sector of the Central Graben is the most notable example (Zoback and Zinke, 2002; Ottemöller et al., 2005; Cesca et al., 2011). Here the effects are manifested as subsidence of the sea bed. Subsidence of 8.26 m had been recorded by 2002, but this could have been much more without a water injection repressurisation scheme (Ottemöller et al., 2005). Musson (2007) remarks that although seismicity in the Central Graben may have increased recently, the Northern North Sea experienced seismicity long before petroleum production and is thus of natural origin. Nevertheless, the Northern North Sea may be experiencing enhanced seismic activity as a result of petroleum production. The spatial correlation of seismicity with the UK's offshore oil and gas fields (Fig. 9) suggests a link between seismicity and offshore

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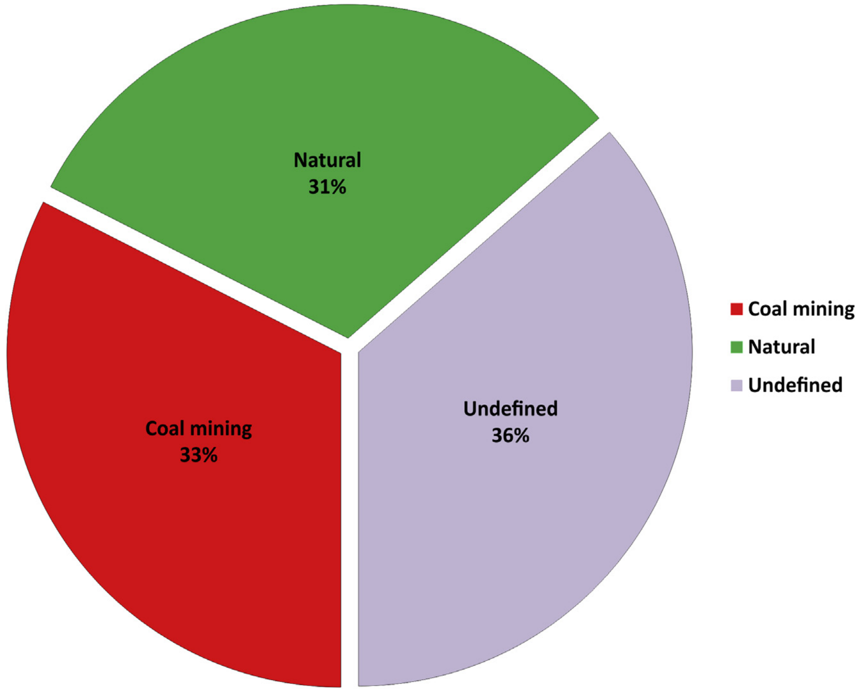

Fig. 6. Pie chart showing the percentage of natural, undefined and coal mining related seismic events in 1985. Our analysis suggests that coal mining related events could have accounted for at least ~33% of all detected onshore UK seismic events in 1985.

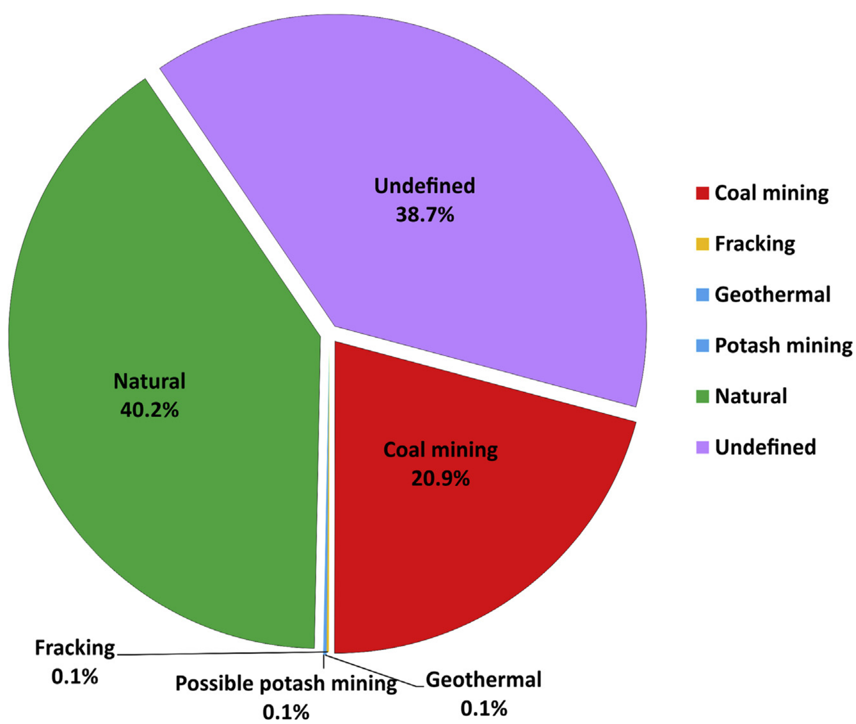

Fig. 7. Pie chart showing the causes of 1769 onshore seismic events with $M_L \geq 1.5$ from 1970–2012. The majority of events are classified as natural or undefined and at least ~21% are thought to be coal mining related. Fracking, geothermal, and potash mining anthropogenic events have been minor contributors to UK seismicity to date.

petroleum production. However, the paucity of the earthquake data hinders more detailed analysis and one has to be cautious that in each case the spatial coincidence means there is indeed causality. We nevertheless attempted a preliminary analysis using the BGS seismic event data in combination with the Department of Energy and Climate Change (DECC) UK petroleum production data for the period 1975–2008. The spatial data suggest there probably is a causal relationship between seismicity and petroleum production/water injection in the North Sea, although links to production and injection volumes are weak based on the data available.

At the Beatrice field in the Moray Firth (Fig. 10a) there have been sixteen detected seismic events within or close to the field

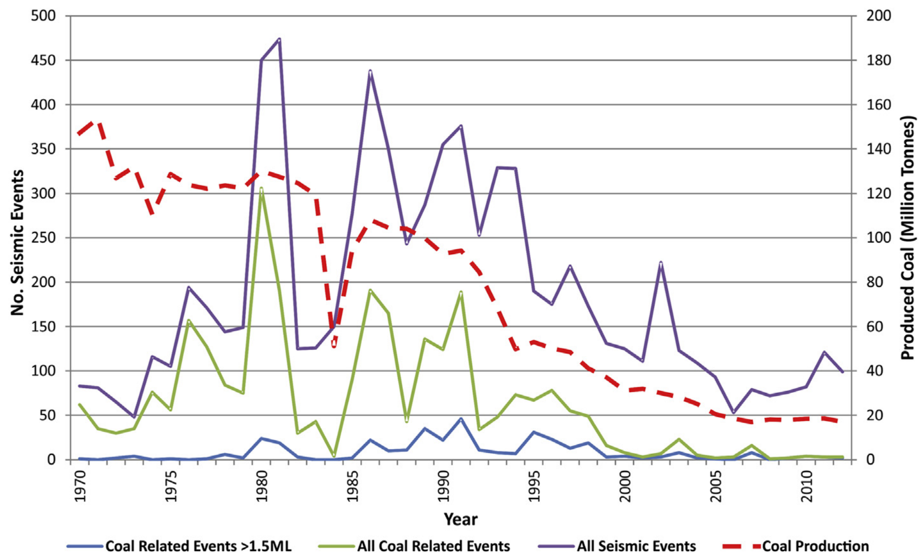

Fig. 8. Graph showing the decline in UK coal production (dotted red line) vs. generally declining numbers of coal mining related earthquakes (blue line – $M_L \geq 1.5$, green line – all detected) for 1970–2012. The large drop in coal production and seismicity in 1984 occurred because of the miners' strike. An increase in seismicity in 1985 may relate to mine flooding and lack of maintenance after numerous mine closures. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

boundaries (Fig. 10b). The surrounding area appears aseismic, increasing confidence that the seismicity is linked to subsurface volume changes from petroleum production. Conversely, when the events were examined in relation to oil production and water injection histories, we observed little correlation. The Britannia field, also situated in the Moray Firth, shows a good spatial correlation to detected events. Seven events have been detected within, or close to, the field boundaries (Fig. 10c). Despite this spatial clustering, a temporal correlation to petroleum production was again unclear.

When the Southern North Sea Gas Province is mapped against seismic event locations it is clear that events cluster around the gas province (Fig. 11a). The surrounding areas of the North Sea are relatively aseismic in comparison. The Leman field in the south of the province shows a spatial coincidence with seismic events, with ten events detected on or within the field boundary (Fig. 11b). This spatial distribution is unlikely to be a coincidence. However, plotting the seismicity and production history on an annual basis failed to reveal any correlation between the two.

6.3. *Fracking*

In the spring of 2011, the first UK multi-stage fracking of a shale rock took place at Preese Hall, Lancashire, in a 1000 m section of the Namurian Bowland Shale. At 2.34 AM on April 1st 2011, the BGS reported an earthquake with M_L 2.3, ~1.8 km from the Preese Hall 1 well and 3.6 km deep. Keele University installed two GURALP 6TD seismometer stations together with two later BGS surface stations to detect possible aftershocks. However, no further earthquakes were detected and fracking recommenced. On May 27th, another earthquake of M_L 1.5 occurred 1.0 km away from the Preese Hall 1 well. Operational activities were suspended.

A total of fifty two earthquakes with waveforms similar to those of April 1st 2011 and May 27th 2011 were detected using correlation techniques. Magnitudes ranged between M_L −2.0 and M_L 2.3. Only two weak events (M_L −1.2 and −0.2) occurred after May 27th and a further small event, with a similar waveform, occurred on August 2nd 2011.

Fracking has very likely already been carried out for the stimulation of some onshore conventional reservoirs in the UK (The Royal Society and The Royal Academy of Engineering, 2012), although there is no published record we are aware of documenting which wells and when it was carried out. Nevertheless, this seems to have had little or no impact in slowing the decline of anthropogenic earthquakes since the mid-1980s (Figs. 8 and 15).

6.4. *Geothermal energy – thermal fractures*

Geothermal projects in low-permeability formations also involve enhancing permeability by fracturing, requiring the injection of large volumes of water. Such projects are currently known as Enhanced Geothermal Systems (Evans et al., 2012). Several EGS test projects have been conducted in the UK in the last 25 years (Younger et al., 2011). The Rosemanowes project in Cornwall (also known as the Camborne School of Mines Hot Dry Rock project) ran from 1978 to 1991. Three wells were drilled to develop a circulation system within the Carnmenellis Granite. Fluid injection in the first two wells was accompanied by thousands of earthquakes (Baria et al., 1985). The first, and largest (M_L 2.0), earthquake to be detected on the BGS network occurred on July 12th 1987 (Turbitt et al., 1987). A further four events in the BGS catalogue are thought to be linked to the project. In total two geothermal energy related earthquakes exceeded M_L 1.5.

6.5. *Lead, copper and tin mining*

The oldest induced or triggered earthquake was probably caused by the collapse of lead mine workings in 1755 in Derbyshire (Bullock, 1755). Bullock (1755) reports a six-inch wide, 150 yard long crack observed at the Earth's surface. There may be more recent examples from the 20th century. For example, in 1999 two seismic events occurred near Redruth, Cornwall, which was a copper-mining town in the 19th Century. The events were small in magnitude and their shallow hypocentre depths suggest that they may have resulted from the collapse of copper mine workings. Camborne, Cornwall, may also have experienced similar mining related seismic events. Six small magnitude ($M_L \leq 0.8$) seismic events in the period 1987–1998 occurred at relatively shallow depths (0.2–1.8 km). Given Camborne's past tin and copper mining history, these events may also have been mining related.

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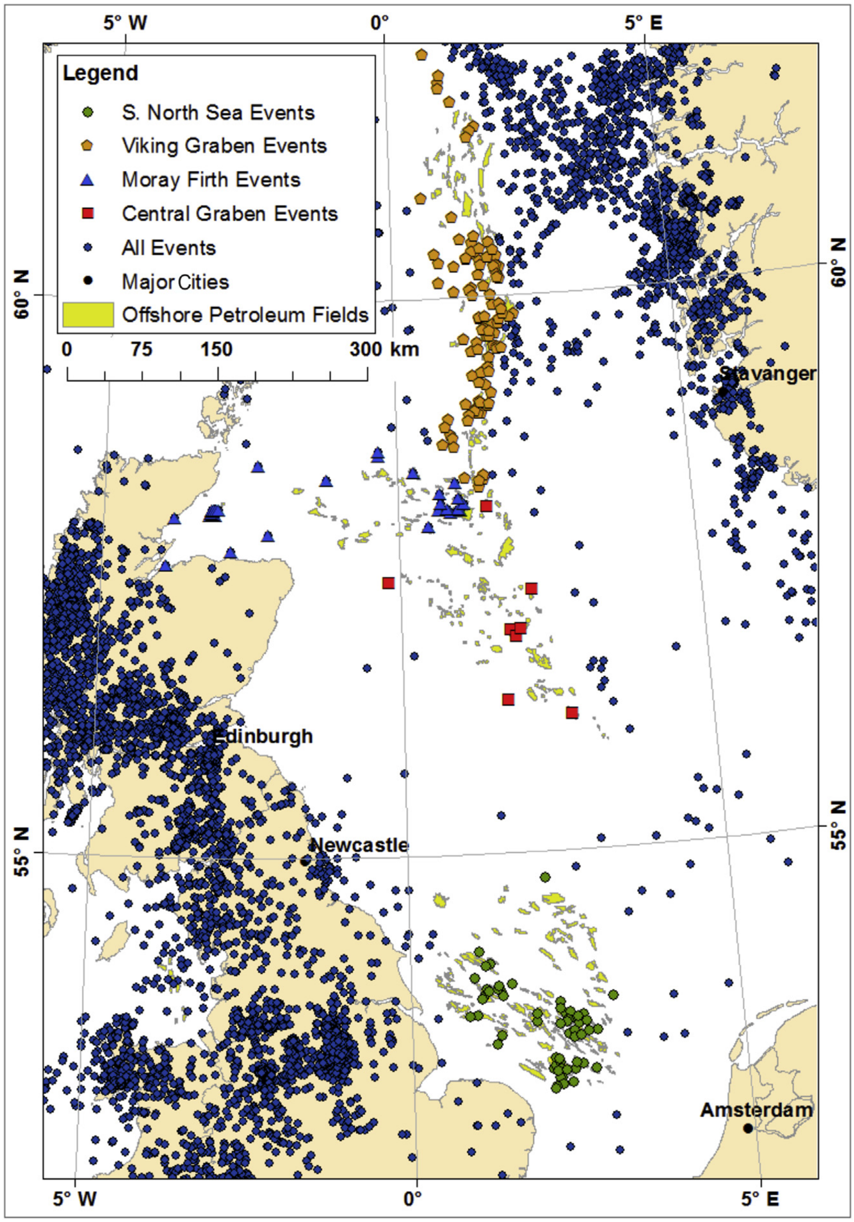

Fig. 9. Map showing the distribution of all recorded Viking Graben events (orange circles), Moray Firth events (blue triangles), Central Graben events (red squares) and Southern North Sea Gas Province events (green circles) in relation to offshore UK oil and gas fields (yellow). Field locations in this figure and subsequent figures from DECC (2015b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

6.6. Potash and salt mining

The term potash refers to a variety of salts that contain potassium in water-soluble form. They are mined primarily for agricultural fertilizer. On September 5th 1989, BGS seismometers detected an event (M_L 2.4) near to Loftus, North Yorkshire (a potash mine location). The observation of strong surface waves suggested that it occurred at shallow depth. However, the event occurred relatively far from the seismic stations and thus analysis was limited and inconclusive (Browitt, 1991; Turbitt, 1991).

7. Seismicity in potential UK shale exploitation areas

7.1. The Weald basin, southern England

The Jurassic rocks of the Weald basin, southeast England, comprise an unconventional shale play (Fig. 12). Potential reservoirs include the Kimmeridge Clay, the Corallian, the Lower Oxford Clay, the Upper Lias, and the Middle Lias (Andrews, 2014). The southeast of England is one of the least seismically active areas in the UK (Fig. 2). Only five seismic events have been detected in the Weald basin shale play in the period 1970–2012. Surface mapped faults generally trend east-west across the area, and most lie in the east of the basin (Fig. 12). Recent seismic reflection data interpretation suggests that this fault zone extends further to the west than previously mapped (Andrews, 2014).

7.2. The Midland Valley basin, Scotland

The BGS have identified four potential reservoirs in the Midland Valley basin. These are the Limestone Coal Formation, the Lower Limestone Formation, the West Lothian

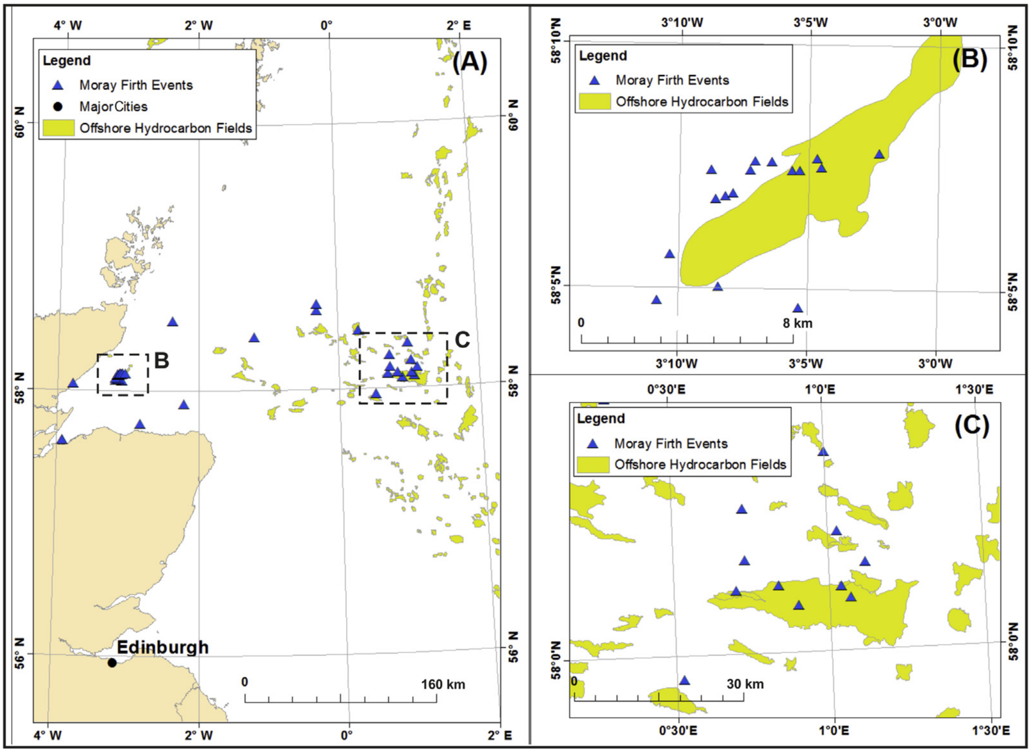

Fig. 10. (a) Map of the Moray Firth showing offshore oil and gas fields (yellow) and detected seismic events (blue triangles) in the Moray Firth. (b) Events clustering around the Beatrice oil field. (c) Events clustering around the Britannia gas field. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

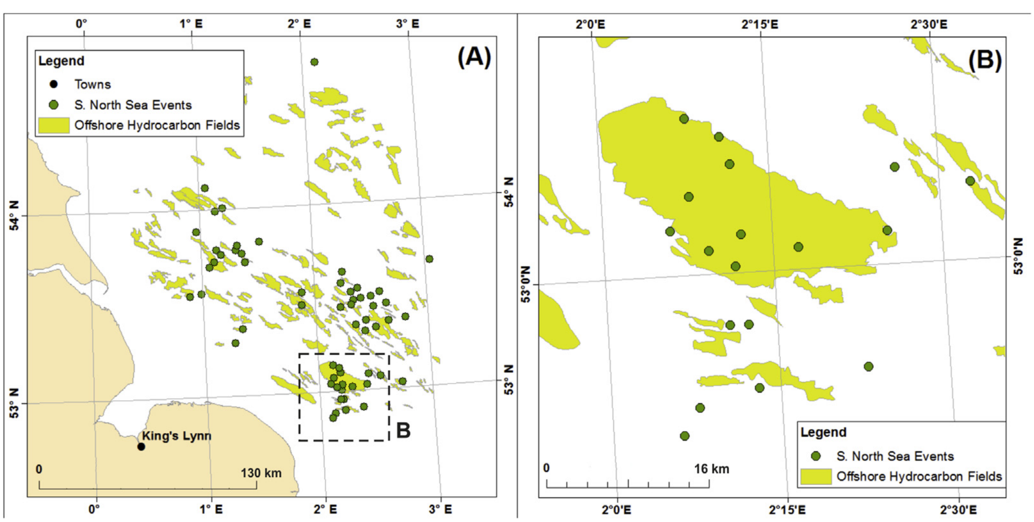

Fig. 11. (a) The Southern North Sea Gas Province (yellow) and seismic event distribution (green circles). (b) The Leman gas field showing ten events within, or close to, the field boundary. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Oil-Shale Unit and the Gullane Unit (Monaghan, 2014). The Midland Valley basin has a much more complex geological history than the Weald basin (Raymond, 1991). This has led to extensive faulting, primarily with trends of northeast-southwest and east-west. The Midland Valley basin is also much more seismically active than the Weald basin. The area has had a long history of coal mining and there are areas where shale gas and oil prospects lie immediately below historical coal fields (Fig. 13).

7.3. The Bowland-Hodder shale units, the midlands and northern England

The Bowland-Hodder shale play includes the East Irish Sea Basin, the Bowland Basin, the Lancashire Coalfield, the Balcon Basin, the Cheshire Basin, the Widmerpool Trough, the Gainsborough Trough and the Cleveland Basin (Andrews, 2013). Numerous faults have been mapped using outcrops and seismic reflection data (Fig. 12). Many of these faults may be critically stressed and

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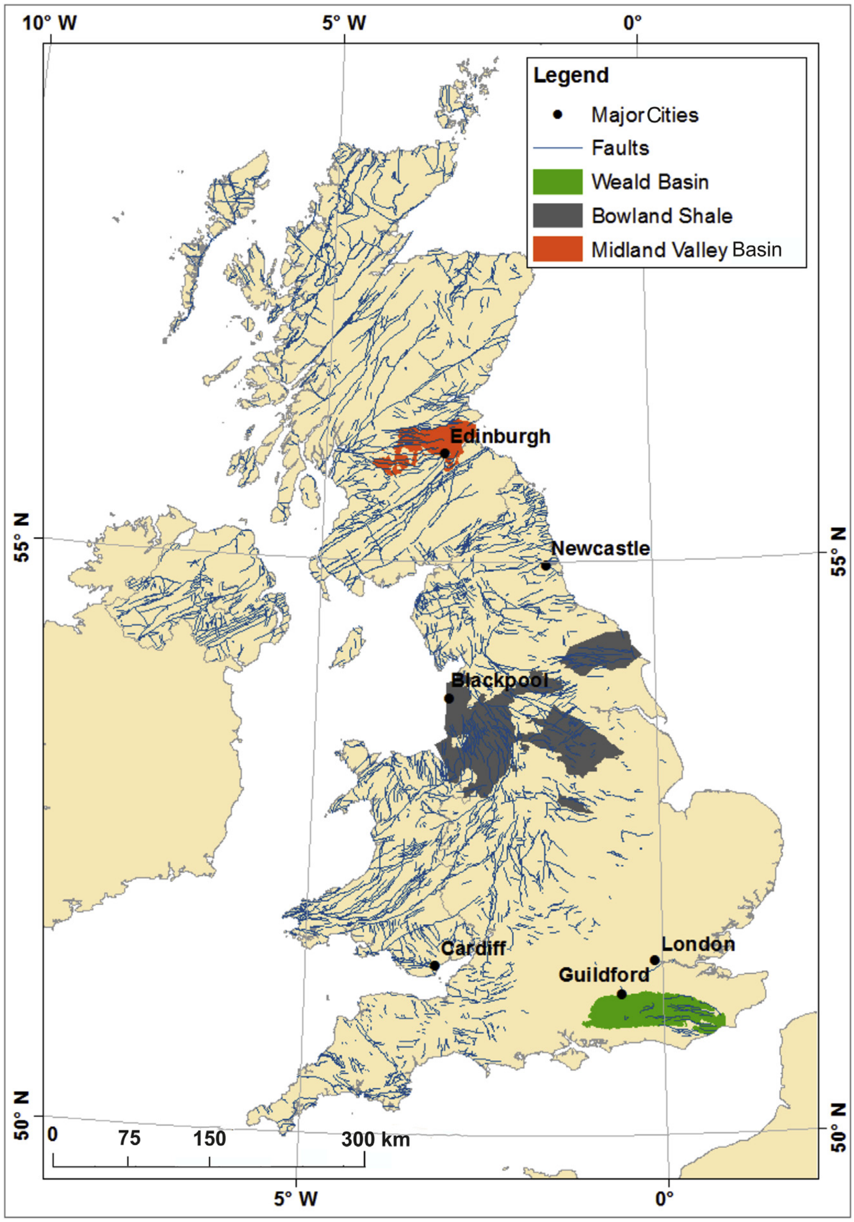

Fig. 12. Major UK shale gas prospects (DECC, 2015c) and surface mapped faults (BGS, 2015).

seismically active based on the number of seismic events that occur across the area. Much of the Bowland-Hodder shale units, like the Midland Valley basin, are situated beneath coal bearing strata which include the Lancashire, Nottinghamshire, Yorkshire, Derbyshire and North Staffordshire coalfields (Fig. 13).

8. Temporal distribution of UK seismicity

The BGS seismic event catalogue for 1970–2012 contains ~8000 onshore events, a sufficient database to estimate the recurrence times of nuisance and potentially damaging earthquakes in the UK. A Gutenberg–Richter plot of cumulative number of events vs. magnitude for events occurring in the time period 1980–2012 is shown in Fig. 14. We chose this time period because examination of similar plots for the four decades 1970–2010 indicated that the decade 1970–1979 has a significantly different distribution (fewer lower magnitude events) from subsequent decades. This is probably a result of fewer seismometers and therefore a higher detection threshold during this decade. Fig. 14 only includes events from the BGS catalogue that occurred in the UK.

The plot (Fig. 14) is constructed in the standard form and as expected for a fractal phenomenon, is approximately linear for magnitudes in the middle of the range. Linearity breaks down below the location threshold, i.e. the smallest magnitude for which the catalogue is complete. Examination of the plot suggests that this is M_L 1.4. Linearity also deteriorates for larger magnitudes. A slight shortfall of events is observed in the range M_L 3.6–4.3 and an excess in the range $M_L > 4.7$. Those earthquakes are few in number and thus provide less-reliable statistical data for estimating earthquake occurrence rate.

The straight line that fits the data best for events with $M_L > 1.4$ is described by:

$$\mathrm{Log}\ N = 4.6 - 0.86M_L \tag{2}$$

where N is the number of earthquakes with $M_L > 1.4$. This

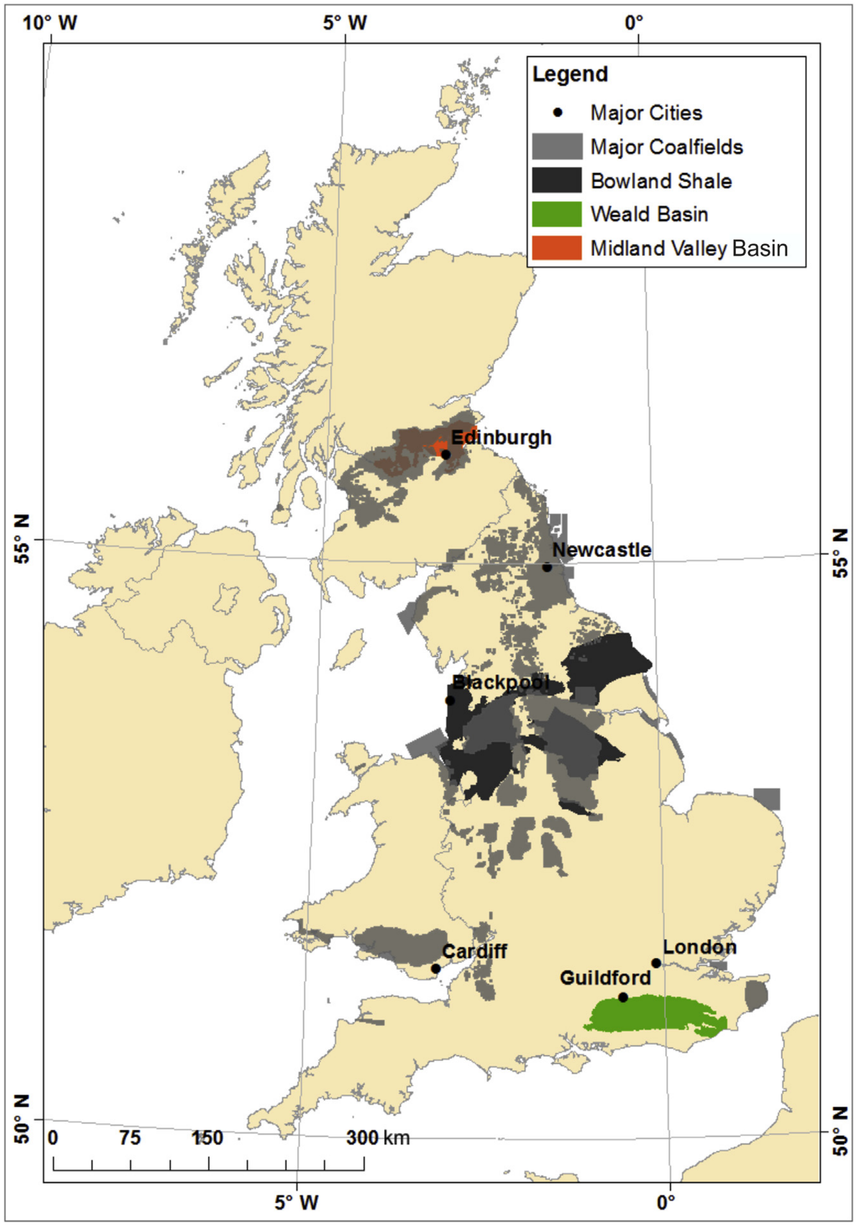

Fig. 13. Major UK shale gas prospects and major coalfields (DECC, 2015a). Significant areas of the Bowland-Hodder and Midland Valley prospects coincide with worked coalfields.

relationship is obtained by weighting most heavily the data for smaller magnitude events, since they are based on larger numbers of earthquakes.

This relationship differs somewhat from that estimated by Musson (1996) which is:

$$\text{Log N} = 3.82 - 1.03M_L \quad (3)$$

This may be attributed to differences in analytical approach. Musson (1996) reviewed magnitude-frequency relations for events occurring since the year 1300. Because of the radical variation in detection threshold with time during this period, Musson (1996) divided events into three groups – those occurring since the year 1300 (for which only earthquakes estimated to be $M_L > 5.4$ were used), those occurring since 1700 (for which only earthquakes estimated to be $M_L > 4.0$ were used), and those occurring since 1970, for which earthquakes with $M_L \geq 3.0$ were used. Musson (1996) combined the data sets, plotting the number of earthquakes per year for each magnitude instead of the traditionally used total number, and fitted a straight line to the data for $M_L \geq 3.0$ using least-squares regression. This method weights every data point equally, regardless of how many earthquakes each is based on.

Of particular interest is the gradient of the line, the so-called “b-value”. Using the method of maximum likelihood (Aki, 1965), we obtain a value of 0.86 ± 0.04 compared with the value of 1.03 obtained by Musson (1996). This gradient is of particular importance because it is often used to make estimates of the rate of occurrence of larger earthquakes obtained by extrapolation. Because we obtain a slightly smaller b-value for earthquakes occurring in the UK, our estimates of the magnitudes of the 100-year and 1000-year earthquakes are higher (Table 3). However, Musson (1996) acknowledges an over prediction from equation (3) and goes on to suggest a revised b-value of 0.94. Error in the b-value estimate of 0.94 is likely to be larger than our error because

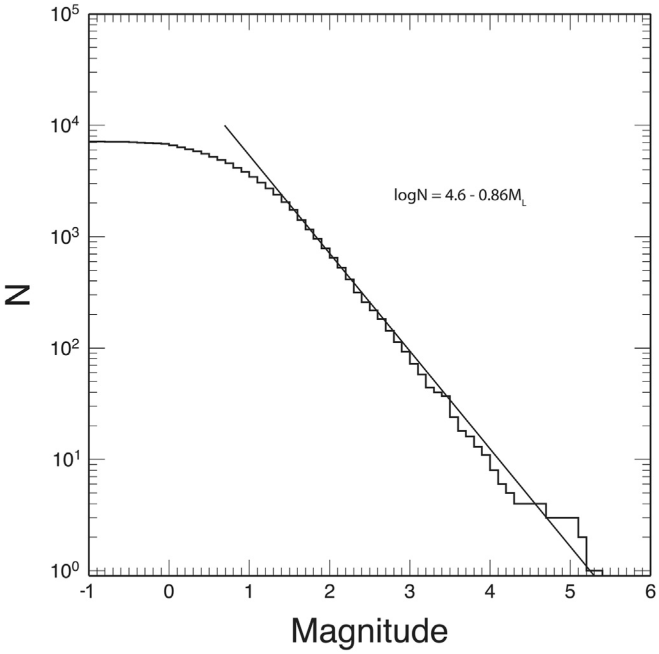

Fig. 14. Gutenberg–Richter plot for seismic events in the UK for the period 1980–2012. The magnitude axis is local magnitudes.

of fewer recorded earthquakes to 1996. Nevertheless, the b-value estimates of 0.86 and 0.94 are not statistically significantly different and therefore neither are the estimated occurrence rates of large earthquakes.

The earthquake occurrence estimates (Table 3) should be viewed as likely statistical maxima, because they do not take account of the breakdown of self-similarity as the maximum magnitude earthquake is approached. It is expected that for every tectonic province there is a maximum magnitude earthquake that can occur. This magnitude is dependent on the maximum length of faults and the thickness of the brittle lithosphere. For the world, the maximum magnitude earthquake is roughly 9.0–9.5 (M_W) (see Bell et al., 2013; their figure 2). For the UK it is much smaller, and estimates in the range M_L 6.0–7.0 have been presented (e.g. Musson, 1996). It is expected that the incidence rates of earthquakes approaching the maximum magnitude fall short of those predicted by simple extrapolation of the Gutenberg–Richter plot.

During the 32-year period 1980–2012, 1644 earthquakes with $M_L \geq 1.5$ occurred, an average of 51 per year. This is compared with the 188 earthquakes with $M_L \geq 1.5$ predicted annually by the relationship of Musson (1996), which does not fit the observed numbers of events. A histogram of numbers of detected events with $M_L \geq 1.5$ (Fig. 15) shows the improvement in location capability toward the end of the 1970s. From the mid-1980s to the 2000s the number of detected events per year generally declines, which may reflect the decline in deep coal mining and the associated reduction in the number of events related to this activity.

Table 3
Frequency-magnitude data for the period 1980–2012.

Earthquake recurrence time, years	Estimated M_L (this analysis)	Actual number observed in the 32-year period 1980–2012	Estimated M_L from Musson (1996)
1	3.6	24	3.7
10	4.8	3	4.7
100	5.9	0	5.6
1000	7.1	0	6.6

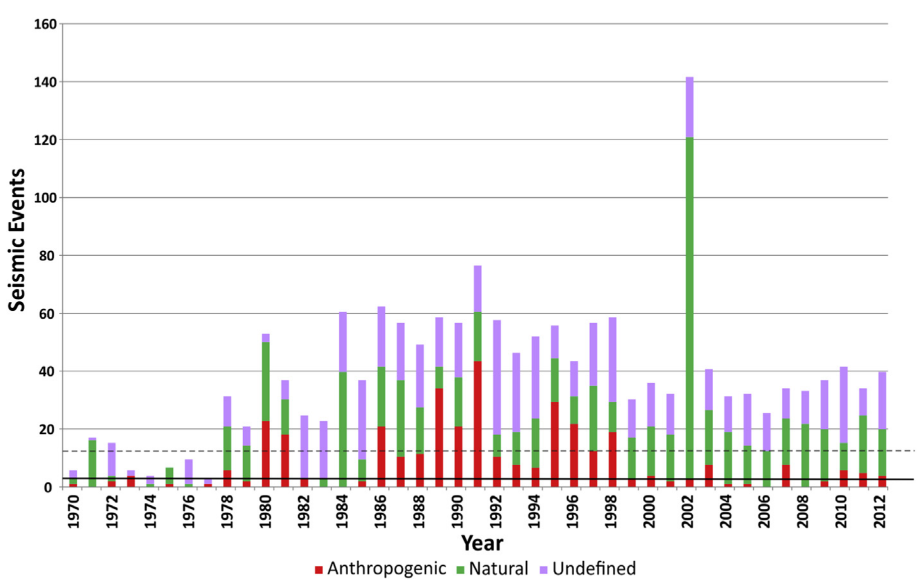

Fig. 15. Histogram showing the annual numbers of different types of seismic events with $M_L \geq 1.5$. Few events were recorded in the 1970s because the seismic network was in an embryonic state. From the 1980s onwards, during which time the network has been essentially complete, the numbers of natural and undefined events have remained relatively constant with the exception of 2002 when the Manchester earthquake swarm occurred. Coal mining related events have particularly reduced in numbers since 1999. From 1999–2012 the rate of anthropogenic earthquakes has typically been three events with $M_L \geq 1.5$ per year. Solid black line – average of three anthropogenic earthquakes per year since 1999. Dashed black line – average of twelve anthropogenic earthquakes per year since 1999, if one assumes 50% of the undetermined events had an anthropogenic origin.

9. Discussion and implications

9.1. Uncertainties

There is of course some uncertainty in categorising the seismicity from 1970–2012 as anthropogenic or natural. Our interpretation of the categorisation has been cautious and therefore unsurprisingly ~39% are assigned as undefined. The estimates of ~21% and ~40% respectively for anthropogenic and natural events are both very likely to be underestimates and some proportion of the 39% should be allocated into each category. Whilst every effort has been made to ensure the correct categorisation of an event, the process used is interpretive based on the criteria we have outlined and we cannot accurately quantify the uncertainty because of the interpretative method employed. Instead we state that the percentages are approximate values.

9.2. The first UK baseline

The level of anthropogenic earthquakes in the UK has been high in the past. Between 1970–2012 at least 21% of detected seismic events with $M_L \geq 1.5$ were probably caused by coal mining (Fig. 7). While significant nuisance has been caused by slow ground deformation associated with the removal of subsurface mass, the direct effects of mining related earthquakes have not caused a significant hazard. Recently the numbers of anthropogenic earthquakes have decreased, probably because of the reduction in deep coal mining. On average since 1999 there have been three anthropogenic related earthquakes ($M_L \geq 1.5$) per year onshore in the UK, but with a wider annual range of between zero and eight (Fig. 15). We propose this as the current UK baseline for anthropogenic seismicity and to our knowledge it is the first of its kind for any nation state. All but two anthropogenic events with $M_L \geq 1.5$ between 1999 and 2012 have been caused by coal mining and this remains the current dominant cause of anthropogenic seismicity in the UK. These events are presumed to be delayed fault reactivation or mine collapse. The other two anthropogenic events during this period were due to fracking in 2011 at Preese Hall, Lancashire.

With more data and analysis it is possible that one could show that some of the undetermined events since 1999 were anthropogenic. If 25% of the undetermined events since 1999 were anthropogenic then the annual range of anthropogenic events would increase to between three and thirteen, with an average of eight per year. If 50% of the undetermined events had an anthropogenic origin then the annual average is twelve per year (Fig. 15).

9.3. Maximum magnitude for UK anthropogenic events

On a geological scale, coal mines are small, shallow features and thus a maximum magnitude must exist for UK coal mining related earthquakes (Styles and Baptie, 2012). The largest probable coal mining related earthquake in this study has a magnitude of M_L 3.1. It has been suggested that this approximate maximum may also apply to fracking operations in the Bowland Shale (Styles and Baptie, 2012).

9.4. Where are the UK's faults?

Fault maps for the UK are available from the BGS, but not all faults have been mapped as they may be blind and therefore are not apparent on the land surface and have not been identified using seismic reflection data. The surface traces of faults may also not be representative of their subsurface location because of the dip of the fault plane. Relative repositioning of the 2002 Manchester earthquake swarm, for example, indicated a previously unknown fault (Baptie and Ottemöller, 2003). Therefore it is possible that there are faults in the UK that could be reactivated that are not documented as yet. The acquisition of high-resolution, 3D seismic reflection data would very likely improve the accuracy of the mapping of subsurface faults.

It may be sensible to deploy local seismic networks in areas of interest prior to drilling and fracking to provide a local baseline of pre-fracking seismicity levels. Data from the fracking operation itself that allows for felt seismicity to be tied back to the injection history will be essential so that some of the criteria outlined by Davis and Frohlich (1993) can be rigorously applied.

10. Conclusions

Over the period 1970–2012 the UK has been prone to anthropogenic seismicity, predominantly due to coal mining. During this period coal mining related earthquakes accounted for at least ~21% of detected onshore events with $M_L \geq 1.5$. Recent shale reservoir fracking operations have introduced a relatively new source of potential anthropogenic earthquakes to the UK. Although fracking related earthquakes tend to be small, the UK is criss-crossed by faults, some of which may be critically stressed. Triggered fault reactivation may result in earthquakes large enough to be at least a nuisance. On average since 1999 there have been three, clear-cut cases of anthropogenic related earthquakes ($M_L \geq 1.5$) per year onshore in the UK, but with a wider annual range of between zero and eight. If 50% of the seismic events ascribed to an undetermined origin were anthropogenic the average increases to twelve per year. At the time of writing these values represent a national baseline for UK anthropogenic earthquakes, prior to the use of fracking for the exploitation of unconventional shale reservoirs.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.marpetgeo.2015.08.023.

References

Aki, K., 1965. Maximum likelihood estimate of b in the formula log N = a−bM and its confidence limits. Bull. Earthq. Res. Inst. Tokyo Univ. 43, 237–239.
Amaru, M.L., Spakman, W., Villasenor, A., Sandoval, S., Kissling, E., 2008. A new absolute arrival time data set for Europe. Geophys. J. Int. 173, 465–472.
Andrews, I.J., 2013. The Carboniferous Bowland Shale Gas Study: Geology and Resource Estimation. British Geological Survey for Department of Energy and Climate Change, London, UK.
Andrews, I.J., 2014. The Jurassic Shales of the Weald Basin: Geology and Shale Oil and Shale Gas Resource Estimation. British Geological Survey for Department of Energy and Climate Change, London, UK.
Arrowsmith, S.J., Kendall, M., White, N., VanDecar, J.C., Booth, D.C., 2005. Seismic imaging of a hot upwelling beneath the British Isles. Geology 33, 345–348.
Baptie, B., 2010. Seismogenesis and state of stress in the UK. Tectonophysics 482, 150–159.
Baptie, B., 2012. UK Earthquake Monitoring 2011/2012. British Geological Survey.
Baptie, B., Ottemöller, L., 2003. The Manchester earthquake swarm of October 2002. Paper Presented at the EGS-agu-eug Joint Assembly, Zurich.

Baria, R., Hearn, K., Batchelor, A.S., 1985. Induced seismicity during the hydraulic stimulation of a potential hot dry rock geothermal reservoir. Paper Presented at the Proceedings of the 4th Conference on Acoustic Emission/microseismic Activity in Geological Structures and Materials. Pennsylvania State University, University Park, Pennsylvania.
BCOGC, 2014. Investigation of Observed Seismicity in the Montney Trend. British Columbia, Canada, Victoria. https://www.bcogc.ca/node/12291/download.
BGS (downloaded 2015). http://www.bgs.ac.uk/products/digitalmaps/dataInfo.html#_625.
Bell, F.G., Cripps, J.C., Culshaw, M.G., Lovell, M.A., 1988. A review of ground movements due to civil and mining engineering operations. Eng. Geol. Spec. Publ. 5, 3–31.
Bell, A.F., Naylor, M., Main, I.G., 2013. Convergence of the frequency-size distribution of global earthquakes. Geophys. Res. Lett. 40 (11), 2585–2589.
Bishop, I., Styles, P., Allen, M., 1993. Mining-induced seismicity in the Nottinghamshire coalfield. Q. J. Eng. Geol. 26, 253–279.
Bott, M.H.P., 1991. Ridge push associated plate interior stress in normal and hot spot regions. Tectonophysics 200, 17–32.
Bott, M.H.P., Bott, J.D.J., 2004. The cenozoic uplift and earthquake belt of mainland Britain as a response to an underlying hot, low-density upper mantle. J. Geol. Soc. 161, 19–29.
Browitt, C.W.A., 1991. UK Earthquake Monitoring 1989/90. British Geological Society.
Browitt, C.W.A., Thomas, C.W., Morgan, S.N., 1985. Investigation of British earthquakes using the national monitoring network of the British Geological Survey. In: Earthquake Engineering in Britain, vol. 33. Thomas Telford Ltd, London.
Bullock, 1755. An account of the earthquake, November 1, 1755, as felt in the lead mines in derbyshire; in a letter from the reverend Mr. Bullock to Lewis Crusius, D. D. F. R. S. Philos. Trans. (1683-1775) 49 (1755–1756), 398–444.
Cesca, S., Dahm, T., Juretzek, C., Kühn, D., 2011. Rupture process of the 2001 May 7 Mw 4.3 Ekofisk induced earthquake. Geophys. J. Int. 187, 407–413.
Chadwick, R.A., 1997. Fault analysis of the Chesire Basin, NW England. Geol. Soc. Lond. Spec. Publ. 24, 297–313.
Chadwick, R.A., Pharaoh, T.C., Williamson, J.P., Musson, R.M.W., 1996. Seismotectonics of the UK. British Geological Survey.
Chiverrell, R.C., Thomas, G.S.P., 2010. Extent and timing of the last glacial maximum (LGM) in Britain and Ireland: a review. J. Quat. Sci. 25 (4), 535–549.
Crampin, S., Jacob, A.W.B., Miller, A., Neilson, G., 1970. The lownet radio-linked seismometer network in Scotland. Geophys. J. Int. 21 (2), 207–216.
Davies, R.J., Foulger, G., Bindley, A., Styles, P., 2013. Induced seismicity and hydraulic fracturing for the recovery of hydrocarbons. Mar. Petroleum Geol. 45, 171–185.
Davis, S.D., Frohlich, C., 1993. Did (or will) fluid injection casue earthquakes? -criteria for a rational assessment. Seismol. Res. Lett. 64 (3–4), 207–224.
de Pater, C.J., Baisch, S., 2011. Geomechanical Study of Bowland Shale Seismicity. Cuadrilla Resources Ltd.
DECC (2015a). https://www.gov.uk/using-coal-mining-information#Available-Coal-Authority-data.
DECC (2015b). https://www.gov.uk/oil-and-gas-offshore-maps-and-gis-shapefiles.
DECC (2015c). https://www.gov.uk/oil-and-gas-onshore-exploration-and-production#resumption-of-shale-gas-exploration.
Donnelly, L.J., 2006. A review of coal mining induced fault reactivation in great Britain. Q. J. Eng. Geol. Hydrogeol. 39, 5–50.
Evans, K.F., Zappone, A., Kraft, T., Deichmann, N., Moia, F., 2012. A survey of the induced seismic responses to fluid injection in geothermal and CO_2 reservoirs in Europe. Geothermics 41, 30–54.
Firth, C.R., Stewart, I.S., 2000. Postglacial tectonics of the Scottish glacio-isostatic uplift centre. Quat. Sci. Rev. 19, 1469–1493.
Foulger, G.R., 1982. Geothermal exploration and reservoir monitoring using earthquakes and the passive seismic method. Geothermics 11, 259–268.
Foulger, G.R., Panza, G.F., Artemieva, I.M., Bastow, I.D., Cammarano, F., Evans, J.R., Hamilton, W.B., Julian, B.R., Lustrino, M., Thybo, H., Yanovskaya, T.B., 2013. Caveats on tomographic images. Terra Nova 25 (4), 259–281.
Galloway, D.D., 2012. Bulletin of British Earthquakes 2011. British Geological Survey.
Goes, S., Govers, R., Vacher, P., 2000. Shallow mantle temperatures under Europe from P and S wave tomography. J. Geophys. Res. Solid Earth (1978-2012) 105 (B5), 11153–11169.
Gölke, M., Coblentz, D., 1996. Origins of the European regional stress field. Tectonophysics 266, 11–24.
Golledge, N.R., 2010. Glaciation of Scotland during the younger Dryas stadial a review. J. Quat. Sci. 25 (4), 550–566.
Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfeß, D., Müller, B., 2008. The World Stress Map Database Release 2008.
Hill, D.P., Reasenberg, P.A., Michael, A., Arabaz, W.J., Beroza, G., Brumbaugh, D., Brune, J.N., Castro, R., Davis, S., dePolo, D., Ellsworth, W.L., Gomberg, J., Harmsen, S., House, L., Jackson, S.M., Johnston, M.J.S., Jones, L., Keller, R., Malone, S., Munguia, L., Nava, S., Pechmann, J.C., Sanford, A., Simpson, R.W., Smith, R.B., Stark, M., Stickney, M., Vidal, A., Walter, S., Wong, V., Zollweg, J., 1993. Seismicity remotely triggered by the magnitude 7.3 Landers, California, earthquake. Science 11 (5114), 1617–1623.
Holland, A., 2013. Earthquakes triggered by hydraulic fracturing in south-central Oklahoma. Bull. Seismol. Soc. Am. 103 (3), 1784–1792.
Jamieson, T.F., 1865. On the history of the last geological changes in Scotland. Q. J. Geol. Soc. 21, 161–204.
Keranen, K.M., Savage, H.M., Abers, G.A., Cochran, E.S., 2013. Potentially induced earthquakes in Oklahoma, USA: links between wastewater injection and the 2011 Mw 5.7 earthquake sequence. Geology 41, 699–702.
Keranen, K.M., Weingarten, M., Abers, G.A., Bekins, B.A., Ge, S., 2014. Sharp increase in central Oklahoma seismicity since 2008 induced by massive wastewater injection. Science 345 (6195), 448–451.
King, G., 1980. A fault plane solution for the Carlisle earthquake, 26 December 1979. Nature 286, 142–143.
Kusznir, N.J., Ashwin, D.P., Bradley, A.G., 1980. Mining induced seismicity in the North staffordshire Coalfield, England. Int. J. Rock Mech. Min. Sci. Geomechanics Abstr. 17, 45–55.
Maillot, B., Nielsen, S., Main, I., 1999. Numerical simulation of seismicity due to fluid injection in a brittle poro-elastic medium. Geophys. J. Int. 139, 263–272.
McGarr, A., Simpson, D., Seeber, L., 2002. Case histories of induced and triggered seismicity. Int. Geophys. Ser. 81 (A), 647–664.
Métivier, L., de Viron, O., Conrad, C.P., Renault, S., Diament, M., Patau, G., 2009. Evidence of earthquake triggering by solid earth tides. Earth Planet. Sci. Lett. 278, 370–375.
Monaghan, A.A., 2014. The Carboniferous Shales of the Midland Valley of Scotland: Geology and Resource Estimation. British Geological Survey for the Department of Energy and Climate Change, London, UK.
Muir-Wood, R., 2000. Deglaciation Seismotectonics: a principal influence on intraplate seismogenesis at high latitudes. Quat. Sci. Rev. 19 (14), 1399–1411.
Musson, R.M.W., 1996. The Seismicity of the British Isles. Global Seismology Group, British Geological Survey.
Musson, R.M.W., 2007. British earthquakes. Proc. Geologists' Assoc. 118, 305–337.
O'Donnell, J.P., Daly, E., Tiberi, C., Bastow, I.D., O'Reilly, B.M., Readman, P.W., Hauser, F., 2011. Lithosphere–asthenosphere interaction beneath Ireland from joint inversion of teleseismic P-wave delay times and grace gravity. Geophys. J. Int. 184, 1379–1396.
Ottemöller, L., Nielsen, H.H., Atakan, K., Braunmiller, J., Havskov, J., 2005. The 7 May 2001 induced seismic event in the Ekofisk oil field, North Sea. J. Geophys. Res. Solid Earth (1978-2012) 110 (B10).
Ottemöller, L., Thomas, C.W., 2007. Highland boundary fault zone: tectonic implications of the Aberfoyle earthquake sequence of 2003. Tectonophysics 430, 83–95.
Pilidou, S., Priestley, K., Debayle, E., Gudmundsson, O., 2005. Rayleigh wave tomography in the North Atlantic: high resolution images of the Iceland, Azores and Eifel mantle plumes. Lithos 79, 453–474.
Pilidou, S., Priestley, K., Gudmundsson, O., Debayle, E., 2004. Upper mantle S-wave speed heterogeneity and anisotropy beneath the North Atlantic from regional surface wave tomography: the Iceland and Azores plumes. Geophys. J. Int. 159, 1057–1076.
Raymond, A.C., 1991. Carboniferous Rocks of the Eastern and Central Midland Valley of Scotland: Organic Petrology, Organic Geochemistry and Effects of Igneous Activity (Doctor of Philosophy. University of Newcastle upon Tyne, p. L3790.
Rawson, P.F., Brenchley, P.J., 2006. The Geology of England and Wales Hardcover.
Redmayne, D.W., 1988. Mining induced seismicity in UK coalfields identified on the BGS National Seismograph Network. Geol. Soc. Lond. Eng. Geol. Spec. Publ. 5 (1), 405–413.
Redmayne, D.W., 1998. Mining-induced earthquakes monitored during pit closure in the Midlothian coalfield. Q. J. Eng. Geol. 31, 21–36.
Saar, M.O., Manga, M., 2003. Seismicity induced by seasonal groundwater recharge at Mt. Hood, Oregon. Earth Planet. Sci. Lett. 214 (3–4), 605–618.
Sigmundsson, F., Einarsson, P., Rögnvaldsson, S.T., Foulger, G.R., Hodgkinson, K.M., Thorbergsson, G., 1997. The 1994-1995 seismicity and deformation at the Hengill triple junction, Iceland: triggering of earthquakes by minor magma injection in a zone of horizontal shear stress. J. Geophys. Res. Solid Earth (1978-2012) 102 (B7), 15151–15161.
Styles, P., Baptie, B., 2012. Induced Seismicity in the UK and its Relevance to Hydraulic Stimulation for Exploration for Shale Gas. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48331/5056-background-note-on-induced-seismicity-in-the-uk-an.pdf.
The Royal Society and The Royal Academy of Engineering, 2012. Shale Gas Extraction in the UK: a Review of Hydraulic Fracturing. Available. http://royalsociety.org/uploadedFiles/Royal_Society_Content/policy/projects/shale-gas/2012-0628-Shale-gas.pdf.
Townend, J., Zoback, M.D., 2000. How faulting keeps the crust strong. Geology 28 (5), 399–402.
Turbitt, T., 1991. Bulletin of British Earthquakes 1989. British Geological Society.
Turbitt, T., Walker, A.B., Browitt, C.W.A., 1987. Perceptible Hydrofracture Seismic Events Caused by the Hot-dry-rock Geothermal Project in Cornwall (G. S. R. Group, Trans.). British Geological Survey.
Wawerzinek, B., Ritter, J.R.R., Jordan, M., Landes, M., 2008. An upper-mantle upwelling underneath Ireland revealed from non-linear tomography. Geophys. J. Int. 175, 253–268.
Westbrook, G.K., Kusznir, N.J., Browitt, C.W.A., Holdsworth, B.K., 1980. Seismicity induced coal mining in stoke-on-trent (U.K.). Eng. Geol. 16, 225–241.
Woodcock, N.H., Strachan, R.A., 2009. Geological History of Britain and Ireland. John Wiley & Sons.
Yerkes, R.F., Castle, R.O., 1976. Seismicity and faulting attributable to fluid extraction. Eng. Geol. 10 (2), 151–167.
Younger, P.L., Gluyas, J.G., Stephens, W.E., 2011. Development of deep geothermal energy resources in the UK. Proc. ICE-Energy 165 (1), 19–32.
Zoback, M.D., Zinke, J.C., 2002. Production-induced Normal Faulting in the Valhall and Ekofisk Oil Fields. In: The Mechanism of Induced Seismicity. Birkhäuser Basel, pp. 403–420.

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